

-1-

## COUNTERSTAGGER COMPRESSOR AIRFOIL

## BACKGROUND OF THE INVENTION

1  
2  
3  
4  
5 **[0001]** The present invention relates generally to gas turbine engines, and, more specifically,  
6 to compressors therein.

7 **[0002]** In a gas turbine engine air is pressurized in a compressor and mixed with fuel in a  
8 combustor for generating hot combustion gases. The combustion gases are discharged  
9 through turbine stages which extract energy therefrom for powering the compressor, and  
10 producing output power for use in driving a fan in an exemplary turbofan aircraft engine  
11 application.

12 **[0003]** A multistage axial compressor includes cooperating rows of stator vanes and rotor  
13 blades which decrease in size to pressurize air in stages. The compressor vanes and blades  
14 have corresponding airfoils which typically vary in configuration as their size decreases from  
15 stage to stage for maximizing performance of the compressor. Compressor performance  
16 includes, for example, efficiency of compression, flow capability, and stall margin, which are  
17 all affected by the configuration of the vanes and blades.

18 **[0004]** More specifically, the flow or pressure distribution of the air as it is being  
19 compressed through the stator vanes and rotor blades is a complex three dimensional flow  
20 field varying circumferentially around the compressor, radially along the span of the vane and  
21 blade airfoils, and axially along the circumferentially opposite pressure and suction sides of  
22 the airfoils

23 **[0005]** The airfoil pressure side is a generally concave surface cooperating with the opposite  
24 suction side, which is a generally convex surface, for efficiently pressurizing the air as it flows  
25 between blades in the axial downstream direction between the leading and trailing edges  
26 thereof. The pressure distribution of the air undergoing compression varies from the radially  
27 inner root of the airfoil to the radially outer tip of the airfoil which is spaced closely adjacent  
28 to a surrounding compressor casing to provide a suitable radial gap or clearance therewith.

29 **[0006]** The airfoil, itself, may be supported from the compressor rotor in any suitable  
30 manner such as being formed integrally therewith in a unitary blisk configuration, or each

-2-

1 rotor airfoil may have an integral platform and dovetail for mounting the compressor blade in  
2 a corresponding dovetail slot formed in the perimeter of the compressor rotor.

3 [0007] A significant feature affecting compressor performance is the radial clearance  
4 provided between the airfoil tips and surrounding casing. The clearance should be as small as  
5 possible to minimize undesirable flow losses therethrough, but must be sufficiently large for  
6 accommodating transient operation of the compressor which may occasionally lead to tip  
7 rubs. In a tip rub, material is removed from the airfoil tip and may accumulate on the inner  
8 surface of the casing. The shortened tip increases the clearance with the casing which  
9 decreases compressor performance, which is further affected by any accumulation of rub  
10 material on the casing which disrupts the smooth flow of air therealong.

11 [0008] Nevertheless, commercial experience of multistage axial compressors in aircraft  
12 turbofan engines confirms long useful lives for the compressor rotor blades and continued  
13 high performance of the compressor. However, the occasional compressor blade tip rubs  
14 increase tip clearances and decrease compressor performance over the useful blade lifetime.  
15 The loss in compressor performance due to tip rubs further reduces performance of the engine  
16 since the pressurized air is used in the combustion process, and energy is extracted from the  
17 combustion gases in the turbines.

18 [0009] Accordingly, it is desired to provide a compressor rotor airfoil having improved  
19 aerodynamic efficiency notwithstanding increased blade tip clearances due to tip rubs.

20

## 21 BRIEF DESCRIPTION OF THE INVENTION

22

23 [0010] A compressor airfoil includes opposite pressure and suction sides joined together at  
24 leading and trailing edges and extending in span between a root and tip. The airfoil includes  
25 stagger increasing above the root and decreasing above a midspan pitch section thereof.

26

## 27 BRIEF DESCRIPTION OF THE DRAWINGS

28

29 [0011] The invention, in accordance with preferred and exemplary embodiments, together  
30 with further objects and advantages thereof, is more particularly described in the following

-3-

1 detailed description taken in conjunction with the accompanying drawings in which:

2 [0012] Figure 1 is a partly sectional, axial projection side view of a row of compressor rotor  
3 airfoils in a multistage axial compressor.

4 [0013] Figure 2 is a isometric view of an exemplary one of the compressor rotor blades  
5 illustrated in Figure 1 in isolation.

6 [0014] Figure 3 is a top radial view of the compressor airfoil illustrated in Figure 2 and taken  
7 generally along line 3-3.

8 [0015] Figure 4 is a graph plotting stagger in degrees over the radial span of the airfoil  
9 illustrated in Figures 1-3 in an exemplary embodiment.

10 [0016] Figure 5 is a graph plotting dihedral angle in degrees along the leading edge over the  
11 radial span of the airfoil illustrated in Figures 1-3 in an exemplary embodiment.

12 [0017] Figure 6 is a graph plotting aerodynamic sweep angle in degrees along the leading  
13 and trailing edges over the radial span of the airfoil illustrated in Figures 1-3 in an exemplary  
14 embodiment.

15

16

#### DETAILED DESCRIPTION OF THE INVENTION

17

18 [0018] Illustrated in Figure 1 is a row of compressor rotor blades 10 suitably mounted to a  
19 compressor rotor 12 of a multistage axial compressor in a gas turbine engine, shown in part.  
20 The compressor has several stages of stator vanes (not shown) cooperating with corresponding  
21 compressor blades which decrease in size in the downstream direction as air 14 is compressed  
22 during operation. The rotor 12 is axisymmetrical around the axial centerline axis 16 of the  
23 engine and supports a full row of the blades 10 within an annular outer casing 18.

24 [0019] Each compressor rotor blade 10 includes an airfoil 20 extending in span along a  
25 radial axis Z between the perimeter of the rotor and the inner surface of the casing 18. The  
26 airfoil may be integrally formed with the rotor 12 in a blisk configuration (not shown), or may  
27 be removably joined thereto in a conventional manner.

28 [0020] For example, each airfoil may include an integral platform 22 which defines the inner  
29 boundary for the air being compressed. An integral dovetail 24 extends from the platform in a  
30 unitary configuration with the blade for being mounted in a complementary dovetail slot in the

-4-

1 perimeter of the rotor. In the exemplary embodiment illustrated in Figure 1, the dovetail 24 is  
2 a circumferential entry dovetail suitably mounted in the perimeter of the rotor.

3 **[0021]** The compressor airfoil 20 is illustrated in a preferred embodiment in Figures 1 and 2  
4 and includes circumferentially or laterally opposite pressure and suction sides 26,28. The  
5 airfoil pressure side is generally concave and precedes the generally convex suction side as the  
6 airfoil rotates in the circumferential direction, represented by the Y axis, atop the rotor. The  
7 axial axis X is parallel with the engine centerline axis and represents the generally  
8 downstream direction of the air 14 as it undergoes compression through the multiple stages of  
9 the compressor.

10 **[0022]** The corresponding surfaces of the pressure and suction sides are joined together at  
11 axially or chordally opposite leading and trailing edges 30,32 and extend in radial span from a  
12 radially inner root 34 at the junction with the platform to a radially outer tip 36.

13 **[0023]** As shown in Figure 1, the airfoil tip 36 is disposed closely adjacent to the inner  
14 surface of the surrounding casing 18 and defines a substantially constant radial clearance or  
15 gap therebetween extending between the leading and trailing edges of the airfoil. The  
16 generally concave configuration of the airfoil pressure side 26, and the generally convex  
17 configuration of the airfoil suction side 28 are conventionally defined for pressurizing the air  
18 14 as it flows downstream between the compressor rotor blades 10 in each stage of the  
19 compressor.

20 **[0024]** The three-dimensional configuration of the airfoil may be defined in accordance with  
21 conventional practice to maximize aerodynamic performance of the compressor including  
22 efficiency, flow, and stall margin. And, the configuration of the airfoil is also designed for  
23 minimizing centrifugal stresses created therein during rotary operation of the blades in the  
24 compressor.

25 **[0025]** For example, conventional compressor rotor blades are designed with varying twist  
26 or stagger from root to tip thereof. The various radial sections of the airfoil have centers of  
27 gravity stacked along a suitable radial stacking axis which may be straight or bowed for  
28 effecting reduced centrifugal stress during operation. The surfaces of the airfoil are disposed  
29 relative to the incident air 14 being pressurized with suitable values of aerodynamic sweep  
30 which varies between the leading and trailing edges and root to tip of the airfoil.

1 [0026] As indicated above, the occasional rubbing of the airfoil tip 36 with the casing 18  
2 may increase the radial clearance therebetween and decrease compressor performance for  
3 conventional compressor rotor blades. In order to reduce the sensitivity of the compressor  
4 airfoil illustrated in Figures 1 and 2 to increased clearance due to tip rubs, and for improving  
5 compressor performance, the airfoil 20 is suitably modified as described hereinbelow.

6 [0027] For example, Figure 3 illustrates a top view of the airfoil illustrated in Figure 2 with a  
7 superimposed rectangular grid over the pressure and suction sides thereof. Each radial section  
8 of the airfoil includes a straight chord 38 extending from the leading edge to the trailing edge  
9 thereof which defines with the axial axis X a twist or stagger angle A. The stagger angle A is  
10 plotted in Figure 4 in accordance with an exemplary embodiment varying in degrees from the  
11 root at zero span to the normalized tip at unity (1.0).

12 [0028] A significant feature of the compressor airfoil illustrated in Figures 1-3 is the  
13 introduction of bowed- or counter-stagger along the span thereof. Preferably, the stagger  
14 increases above the root 34, and decreases above a midspan pitch section 40.

15 [0029] In a conventional compressor rotor airfoil, the stagger angle typically increases from  
16 root to tip of the blade. The desired stagger angle is primarily controlled by the desired  
17 pressure distribution in the air being pressurized which varies from root to tip of the airfoil.

18 In contrast, the stagger angle of the airfoil illustrated in Figures 2 and 3 increases in  
19 magnitude from a minimum value at the root 34 to a larger value at the pitch section 40, and  
20 decreases in magnitude above the pitch section toward the root stagger magnitude.

21 [0030] In the exemplary graph illustrated in Figure 4, the stagger angle has a minimum  
22 value of 40 degrees at the airfoil root and increases to a maximum value of about 47 degrees  
23 above the pitch section. From its maximum value the stagger angle decreases to the airfoil tip  
24 which has a stagger angle of 43 degrees which is slightly greater than the stagger angle at the  
25 root. The maximum stagger angle is preferably located above the midspan pitch section of the  
26 airfoil to promote the desired pressure distribution over the airfoil span. In the exemplary  
27 embodiment illustrated in Figure 4, the maximum stagger value is located in the range of  
28 about 60%-85% span from the airfoil root.

29 [0031] The introduction of the reverse or counterstagger in the compressor airfoil above its  
30 pitch section results in the distinctive configuration of the airfoil illustrated in Figures 2 and 3.

-6-

1 The counterstagger in the outer span of the airfoil substantially reduces the blade tip stagger  
2 over that found in conventional compressor airfoils for significantly reducing clearance  
3 sensitivity due to tip rubs as confirmed by three-dimensional computational fluid dynamic  
4 analyses. Rotor blade aerodynamic efficiency is improved at nominal clearance levels, and is  
5 significantly improved at deteriorated clearance levels following tip rubs. Analyses also  
6 confirm improved flow pumping with the deteriorated tip clearances. And, improvement in  
7 stall margin may also be possible.

8 [0032] The counterstagger is introduced or manifested in the airfoil illustrated in Figures 2  
9 and 3 primarily along the leading edge 30 relative to the trailing edge 32. The trailing edge is  
10 generally straight from root to tip, whereas the leading edge 30 includes a distinctive concave  
11 bow along the radial span of the suction side 28, with the root and tip following in movement  
12 the pitch section 40 of the airfoil as it rotates in the tangential or circumferential Y direction  
13 illustrated in Figure 3.

14 [0033] The introduction of reduced or lower blade tip stagger in the compressor airfoil  
15 illustrated in Figures 2 and 3 facilitates the introduction of increased tip leading edge dihedral.  
16 Tip dihedral is identified in Figure 2 as the angle B between the local surface of the airfoil  
17 and the surrounding casing 18 illustrated in Figure 1. Tip dihedral is a conventional  
18 parameter, with zero tip dihedral resulting in a blade tip which is oriented normal or  
19 perpendicular to the casing. Positive tip dihedral is achieved when the pressure or concave  
20 side, or both, of the blade tip forms an acute angle with the surrounding casing.

21 [0034] Figure 5 is a graph of an exemplary profile of the dihedral angle B along the leading  
22 edge of the airfoil illustrated in Figures 1-3 relative to the surrounding casing in which the  
23 dihedral angle increases above the pitch section to a maximum value at the airfoil tip 36.

24 [0035] As shown in Figure 5, the dihedral angle above the pitch section is positive and  
25 opposite to the dihedral angle between the root and pitch sections which is primarily negative.  
26 Preferably, the dihedral angle along the airfoil leading edge 30 at the tip 36 is greater in  
27 magnitude than below the pitch section 40. In the exemplary embodiment illustrated in Figure  
28 5, the dihedral angle varies from zero at the airfoil root to a maximum negative value of about  
29 -7 degrees at about 25% span returning to a zero value below the pitch section at about 40%  
30 span, and then increasing in magnitude to a maximum positive value of about 25 degrees at

-7-

1 the airfoil tip at 100% span.

2 [0036] The dihedral angle B cooperates with the stagger angle A, both of which vary along  
3 the airfoil leading edge 30 to bow the airfoil leading edge concave in span along the suction  
4 side 28. The cooperation of the dihedral and stagger permit desirable positive dihedral along  
5 the airfoil tip with a maximum value at the airfoil leading edge, and relatively small but still  
6 positive magnitude of dihedral at the airfoil trailing edge. Correspondingly, a negative value  
7 of dihedral is provided immediately above the airfoil root, and along with the counterstagger  
8 in the airfoil effects the distinctive counter bowed leading edge illustrated in Figures 2 and 3.

9 [0037] Figures 3 and 5 illustrate a preferred configuration of the dihedral angle being  
10 unidirectional with the same positive magnitude along the airfoil tip 36 from the leading edge  
11 30 to the trailing edge 32. In this way, undesirable negative dihedral is not found at the airfoil  
12 tip for improving aerodynamic performance thereof, including performance following  
13 occasional tip rubs.

14 [0038] The compressor airfoil illustrated in Figure 1 also includes aerodynamic sweep C  
15 which is a conventional term of art. The counterstagger and tip dihedral permit a new  
16 introduction of forward or negative aerodynamic sweep at both the leading and trailing edges  
17 30,32 of the airfoil tip 36 for further improving aerodynamic performance of the compressor  
18 airfoil.

19 [0039] Figure 6 is an exemplary graph of the aerodynamic sweep angle C in degrees for the  
20 leading and trailing edges 30,32 of the airfoil illustrated in Figure 1 along the radial span  
21 thereof. Negative or forward aerodynamic sweep is introduced at the airfoil tip along both the  
22 leading and trailing edges, with the sweep having a larger magnitude at the trailing edge. And,  
23 aft or positive aerodynamic sweep is introduced in the airfoil from the root 34 to the pitch  
24 section 40, and further radially outwardly to just below the airfoil tip along both the leading  
25 and trailing edges. Along the leading edge 30, the sweep transitions from positive to negative  
26 at about 90% span, and along the trailing edge, the sweep transitions from positive to negative  
27 at about 80% span.

28 [0040] Figure 1 illustrates an axial projection view, or meridional view of the airfoil. The  
29 airfoil is shown with a concave axial projection along the leading edge 30, with the root 34  
30 and tip 36 extending forward of the pitch section 40 along the leading edge. In this axially

-8-

1 bowed or concave leading edge projection, the airfoil outer span is axially forward of the  
2 midspan region and permits the introduction of the aerodynamically favorable forward blade  
3 tip sweep at both the leading and trailing edges. Furthermore, the axially forward airfoil tip  
4 section permits the trailing edge dihedral at the tip to maintain a favorable positive value, and  
5 thusly avoiding undesirable negative dihedral along the airfoil tip.

6 [0041] As indicated above, compressor rotor airfoils are complex and sophisticated  
7 three-dimensional elements typically designed with various compromises for the competing  
8 demands of aerodynamic performance and mechanical strength. Stagger, dihedral, and  
9 aerodynamic sweep are all conventional features used in designing modern compressor rotor  
10 blades as indicated by the exemplary references of record, incorporated herein by reference.

11 [0042] However, the exemplary compressor rotor blade illustrated in Figures 1-3 includes  
12 distinct configurations of stagger, dihedral, and aerodynamic sweep which are used to  
13 advantage in a cooperation for enhancing compressor performance not only with a nominal  
14 clearance with the compressor casing, but after increased clearance following occasional tip  
15 rubs in extended use of the blade in a gas turbine engine.

16 [0043] The introduction of specific forms of stagger, dihedral, and aerodynamic sweep at the  
17 compressor blade tip illustrated in the figures is blended with the stagger, dihedral, and sweep  
18 in the inner span portion of the airfoil resulting in a distinctive overall configuration and  
19 corresponding performance enhancement.

20 [0044] While there have been described herein what are considered to be preferred and  
21 exemplary embodiments of the present invention, other modifications of the invention shall be  
22 apparent to those skilled in the art from the teachings herein, and it is, therefore, desired to be  
23 secured in the appended claims all such modifications as fall within the true spirit and scope of  
24 the invention.

25 [0045] Accordingly, what is desired to be secured by Letters Patent of the United States is  
26 the invention as defined and differentiated in the following claims in which we claim: